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Thick Film Thermocouple Gauges for Roughened Model Heat Flux Measurements

Prepared by K. E. STARNER and R. L. VARWIG
Aerodynamics and Propulsion Research Laboratory

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FOREWORD

The report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-69-C-0066.

This report, which documents research carried out from February 1969 to May 1969, was submitted on 1 October 1969 to Lieutenant Edward M. Williams, Jr., SMTAE, for review and approval.

Approved

Walter R. Warren

Walter R. Warren, Director
Aerodynamics and Propulsion
Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the stimulation and exchange of ideas.

Edward M. Williams Jr

Edward M. Williams, Jr.
Lieutenant, United States Air Force
Project Officer

ABSTRACT

The study of wall roughness effects on model heat transfer in high Reynolds number shock tunnel flows of a few milliseconds duration requires the use of a rugged, fast-response calorimeter of known surface roughness. Models constructed of continuous thin copper sheeting over a solid insulator substrate with rear thermocouples attached were developed for this purpose. The surface of the copper can be roughened as required and thus forms both an unbroken model surface segment and a heat flux calorimeter. Conditions of heat flux and tunnel test time under which the gauge is useful are shown by analysis. Results from calibration experiments and shock tunnel tests are discussed.

CONTENTS

FIGURES

NOMENCLATURE

C_1	Constant
C_2	Constant equal to $\pi/2\theta_M$
c_p	Specific heat
E	Ratio q_L/q_I
h	Roughness height
k	Thermal conductivity
q	Heat Transfer rate, Btu/sec
$\dot{q}$	Heat flux, Btu/ft^2-sec
R	Model radius
T	Temperature
V	Output voltage
W	Model width
x	Distance from model stagnation point measured along model surface
α	Thermal diffusivity, $k/\rho c_p$
δ	Film thickness
θ	Body angle
ρ	Density
τ	Time

Subscripts

I	Input
L	Loss by conduction
r	Response
M	Maximum
x	Along model surface

I. INTRODUCTION

Surface roughness effects have been shown to be significant in prediction of heat transfer rates to bodies in high Reynolds number flows (Refs. 1 and 2). Such roughness at high Reynolds number has the effect of producing large increases in surface heat flux compared with smooth wall values (Refs. 1-4). Recently, such effects have become of interest in the prediction of ablation rates and shape change of high-speed reentry vehicle nose tips (Ref. 3).

Much work has been done for the case of the laminar boundary layer, and it is well known that maximum heat flux occurs at the stagnation point of a sphere in such a flow. However, less information is available for the case of a turbulent boundary layer, where at sufficiently high Reynolds number the heat flux is expected to be a maximum in the vicinity of the sonic point (Refs. 5 and 6). The experimental study of heat flux to such a body and its variation with roughness and angular location from the stagnation point may require special instrumentation techniques, because of limitations imposed by the necessity for carefully controlling the model surface roughness.

This report describes the development and calibration of rough wall heat flux gauges for application to high Reynolds number short-duration shock tunnel flows. Response and test time limitations of the gauge are analyzed, and special features for application to rough wall measurements are discussed. A gauge concept is introduced that uses the fast response time of the thick film gauge together with the continuous unbroken surface construction required for the study of surface roughness effects.

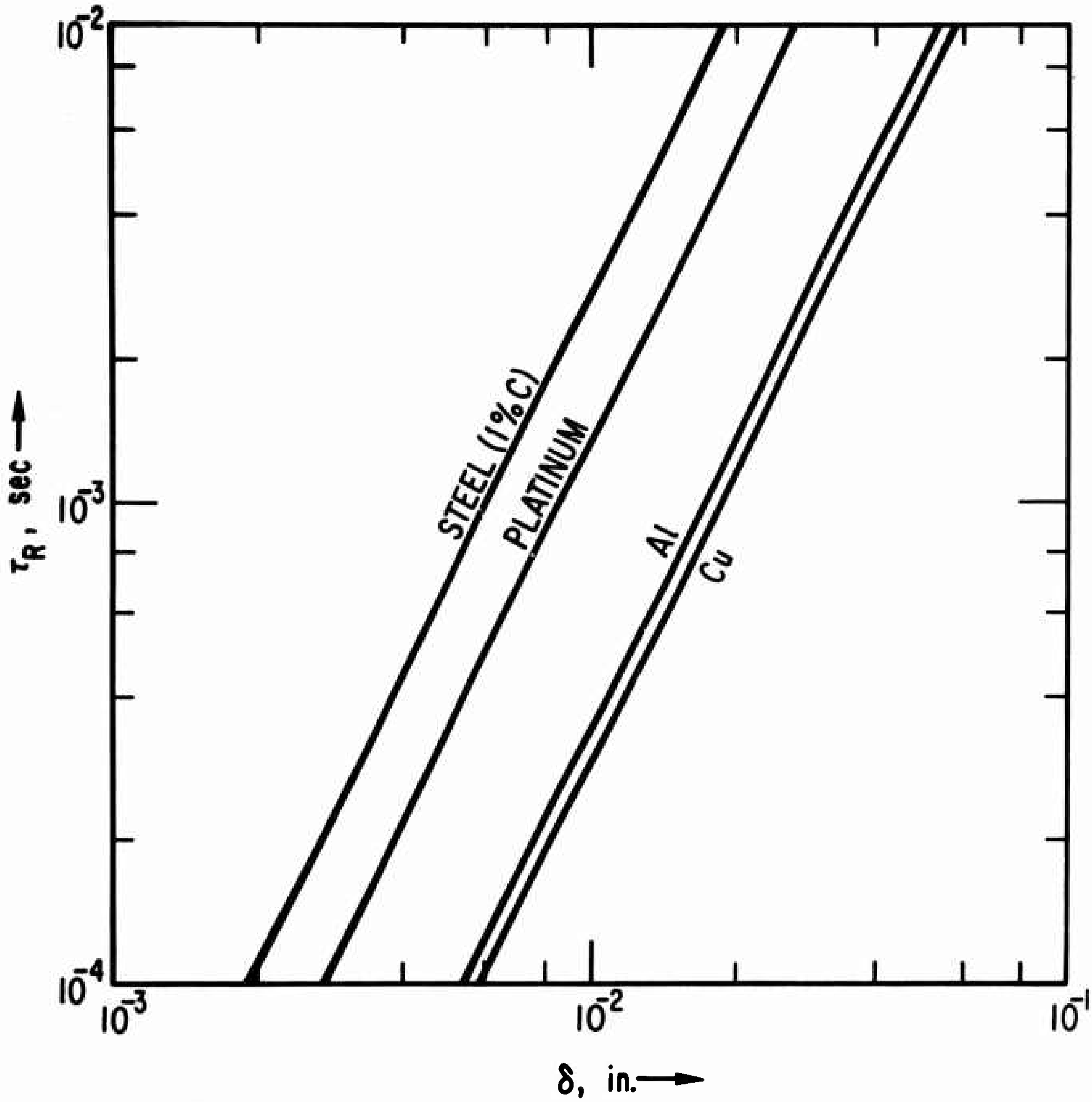

Figure 1. Response Time Based on Film Thickness

II. GAUGE DESIGN CONSIDERATIONS

A study of calorimeter gauges for measurement of heat flux in short duration flows is found in Ref. 7. Calculations are presented for both thin and thick film gauges. The thin-film resistance gauge measures the surface temperature rise of a model substrate, whereas the thick film gauge is essentially a low mass slug calorimeter where heat flux is proportional to the change of average film temperature with time, as shown in Eq. (1).

$$\dot{q} = \delta \rho c_p \frac{dT}{d\tau} \tag{1}$$

Of the two gauge types, the thick film type mechanically best lends itself to a surface roughening scheme and allows determination of average heat flux to the gauge surface. The flows of interest in this study are of a time duration less than 5 msec with a surface roughness height range of 1 to $4 \times (10)^{-3}$ in. (order of the boundary layer thickness) required. These two requirements provide design guidelines for gauge response time and thickness.

The thick film gauge can normally be constructed as a high-current-resistance gauge or as a rear-mounted temperature sensor gauge (Ref. 7). With surface roughness of a few mils required (thus requiring $\delta \gtrsim 0.010$ in. for $\delta > h$) and with fast response time necessary, only a gauge constructed of a material of high α , such as copper or aluminum, can be used. This is shown in Figure 1, where response time τ_r based on film thickness is shown for several materials according to

$$\tau_r = 0.5 \left(\frac{\delta^2}{\alpha}\right) \tag{2}$$

as shown in Ref. 8. It is seen that for $\delta \approx 0.010$, a response time based on thickness of about 0.25 msec is obtained for copper. A gauge of this thickness composed of copper or aluminum is not suitable for use as a resistance type gauge because of its low electrical resistivity, based on the calculations of Ref. 9. Thus, the rear-surface-mounted temperature sensor concept appears most promising. Such gauges can be equipped with either rear-mounted thermocouples or rear-mounted resistance gauges (Ref. 10). The thermocouple gauge

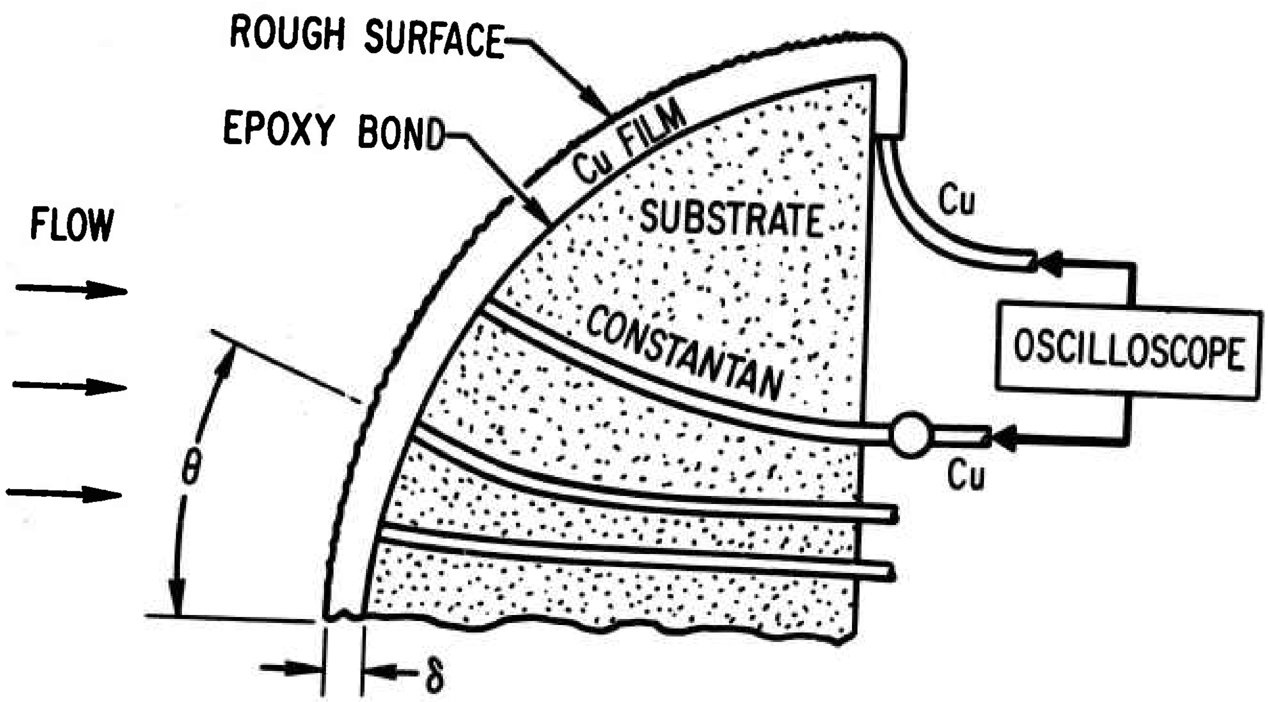

Figure 2. Thin Film Thermocouple Gauge Construction

is of simple, rugged construction and lends itself well to high-pressure instrumentation, since installation of such a sensor requires little void volume behind the gauge film. However, since the resistance thermometer concept produces a high output signal, it should be given consideration wherever possible.

For the present study, the thick film thermocouple gauge of copper construction with a rear-mounted constantan wire was chosen. Figure 2 shows the gauge construction that can be applied to either two-dimensional or axisymmetric bodies. Note that two features important to the study of small-scale surface roughness effects are incorporated in this concept: (1) the model surface is unbroken from the stagnation point to the edge of the model, thus allowing a uniform roughness (with no surface cracks) to be applied over the entire flow path; and (2) the gauge is rigidly mounted on a solid substrate, thus preventing gauge surface fluctuation that must be held to values of less than the roughness height. This type of gauge is quite similar to the thin-skinned calorimeter discussed in Ref. 11 in that both concepts feature an unbroken surface and use a thermocouple sensor. They differ mainly in that the present instrument uses a solid backing for higher pressure testing. The solid insulator back thermally influences the gauge and limits its useful test time (see Section III). Within the limitations explained below, such a gauge should be useful in both impulse tunnel and steady state facilities, provided that rapid exposure to the flow is obtained in all cases.

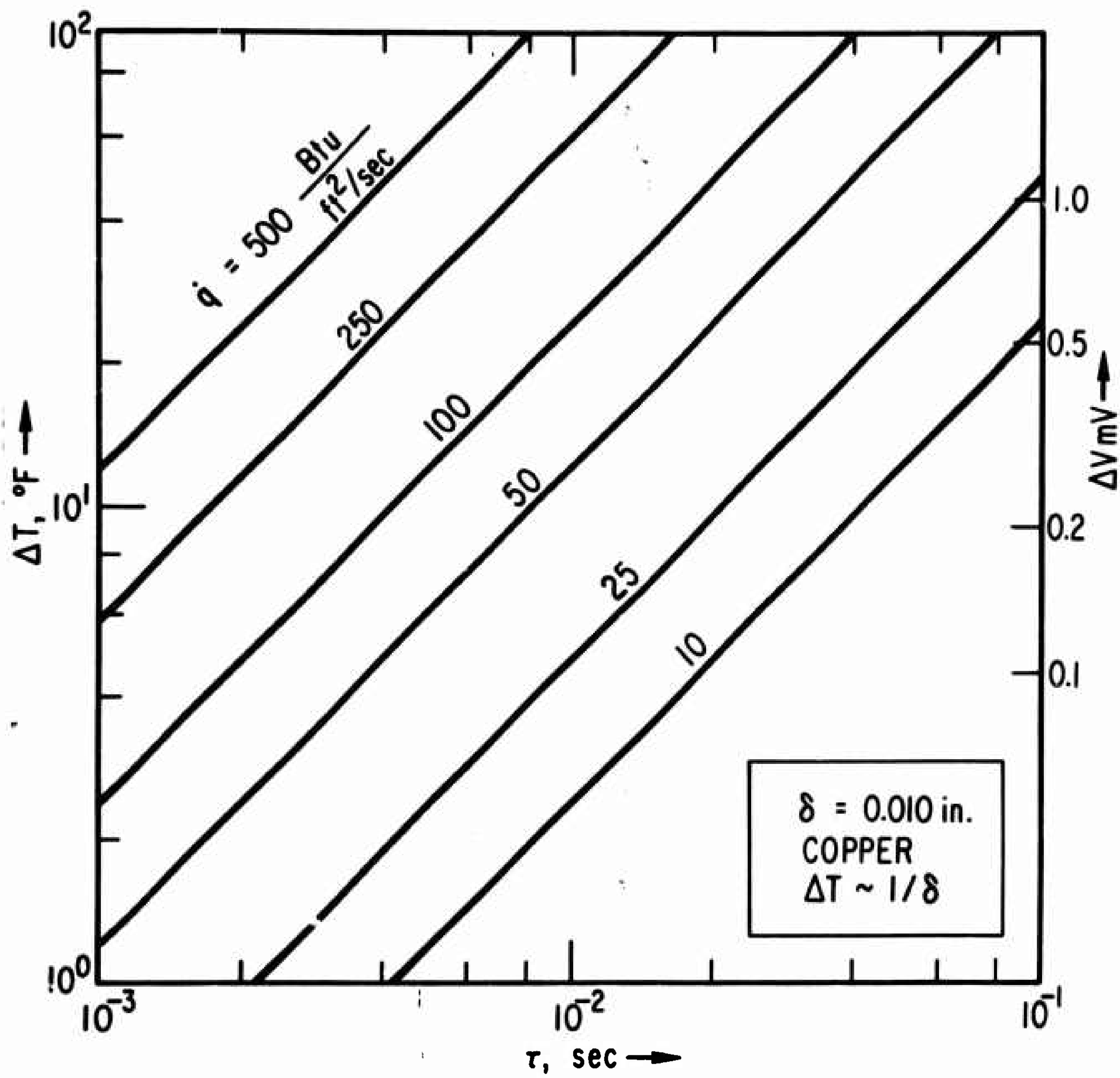

Figure 3. Film Temperature and Gauge Output for a Range of Test Conditions

III. GAUGE LIMITATIONS

As mentioned earlier, a thick film thermocouple gauge does not have an output signal as high as would be obtained if a resistance thermometer sensor were used to sense film temperature. The average gauge temperature and corresponding output from the copper-constantan thermocouple is shown in Figure 3 for a film of 0.010-in. thickness and a range of heat flux. It is seen that, for test times of a few milliseconds and at heat flux values around 100 Btu/ft^2-sec, one can obtain signals in the 0.1 to 1 mV range.

The usable test time of this type of gauge is limited because heat is lost to the film substrate at increasing rates as the film itself gains temperature during testing. Such effects were analyzed in Ref. 7, and Figure 4 is based on calculations made in that report, where it is shown that heat losses are a function of the ratio of the $k\rho c_p$ products of film and substrate. Figure 4 shows that a 0.010-in.-thick copper gauge experiences less than 5% heat loss at the interface after 3 msec if it is mounted on a plastic substrate, but 7.5% if mounted directly on pyrex. As shown in the figure, longer test times may be obtained with thicker gauge films. If long flow times are available, τ_r can be longer, and a thicker gauge is often more suitable (Figure 1). One must be assured that any of the insulator substrate not covered by the thick film sheeting is not overheated in tests of long flow times. The surface temperature of such a model surface can be estimated by use of the one-dimensional equation of heat conduction in a semi-infinite slab, as follows.

$$\Delta T = \frac{2q\sqrt{\tau}}{\sqrt{\pi k\rho c_p}} \qquad (3)$$

The heat flux gradients over the surface of a continuous thick film (or thin skinned) gauge result in temperature gradients within the film and can lead to thermocouple errors if not taken into consideration, since gauge surface temperatures, and therefore surface temperature differences, increase with time of gauge exposures. It is possible to estimate the magnitude of this effect for the simple case of a two-dimensional model by computing the ratio of heat entering the gauge q_I at a given x from the stagnation point to

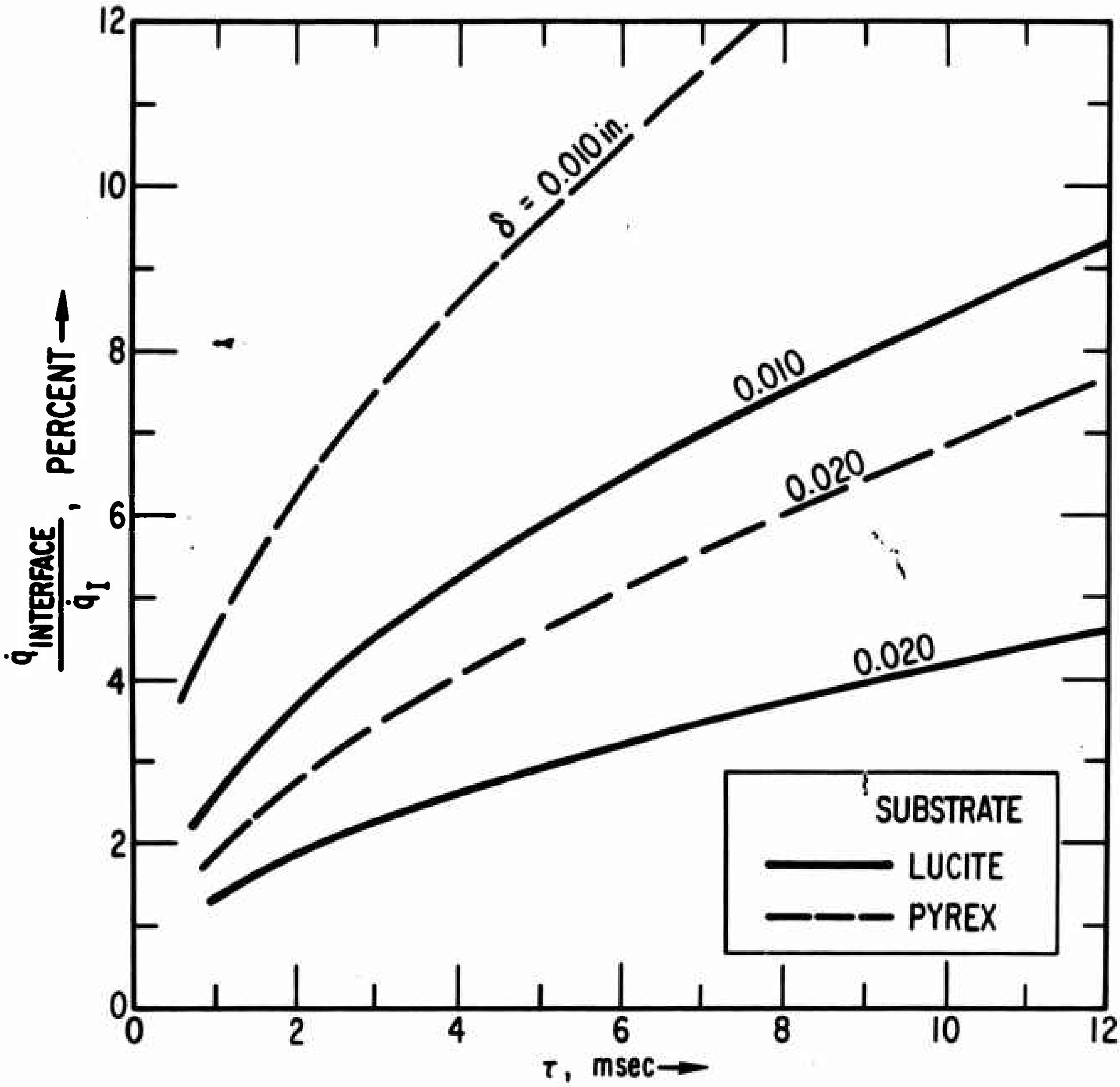

Figure 4. Heat Flux at Interface of Film Substrate

the linear conduction loss q_L at that location. If such conduction loss is not present, the average local temperature is given by

$$T = \frac{1}{\delta}\int_0^{\tau} \frac{\dot{q}_I d\tau}{\rho c_p} \approx \frac{\dot{q}_I \tau}{\delta \rho c_p} \tag{4}$$

The conduction loss away from or into a surface element dx within the film material is given by

$$q_L = k\delta W \left(\frac{d^2T}{dx^2}\right) dx \tag{5}$$

for a surface with negligible gradients in the δ direction ($\tau \gg \tau_r$). The heat entering the element by convection from the freestream is

$$q_L = \dot{q}_I W dx \tag{6}$$

Combining Eqs. (4), (5), and (6) and forming the ratio $q_L/q_I = E_x$, we get

$$E_x = \frac{\alpha\tau}{\dot{q}_I} \left(\frac{d^2\dot{q}_I}{dx^2}\right) \tag{7}$$

Thus, an estimate of the conduction error can be made if one has a knowledge of the surface heat flux distribution and test time of interest.

For example, for the case of turbulent boundary layer flow, Ref. 5 indicates that one might expect a smooth heat flux distribution of the form

$$\dot{q}_I/\dot{q}_{STAG} = 1 + C_1 \sin \frac{C_2 x}{R} \tag{8}$$

in regions away from the stagnation point, which gives a heat flux maximum equal to $\dot{q}_{STAG}$ $(1 + C_1)$ at a body angle θ_M where $C_2 = \pi/2\theta_M$. Using this sample distribution in Eq. (7) gives

$$E_x = \alpha\tau\left(\frac{C_2}{R}\right)^2 \left[\frac{C_1 \sin C_2 x/R}{1 + C_1 (\sin C_2 x/R)}\right] \tag{9}$$

Figure 5 shows the magnitude of the conduction error for a copper film material with $C_1 = 1.0$, such that $\dot{q}_M = 2\ \dot{q}_{STAG}$, and $C_2 = 2.25$, such that $\dot{q}_M$ occurs at a body angle of 40 deg. The losses are seen to be quite negligible for test times of many milliseconds for a model of 1-in. radius.

The attachment of a thermocouple to the gauge material can influence the response time of the resultant gauge. Reference 12 presents calculations useful for estimating the influence of this effect. In general, it is shown that one should attempt to have the thermocouple wire diameter much smaller than the film thickness, $(k\rho c_p)_{T.C.} < (k\rho c_p)_{Film}$, and $\tau_r < \tau$ for good gauge design. These conditions are met with the combination of copper film and constantan wire used in this experiment.

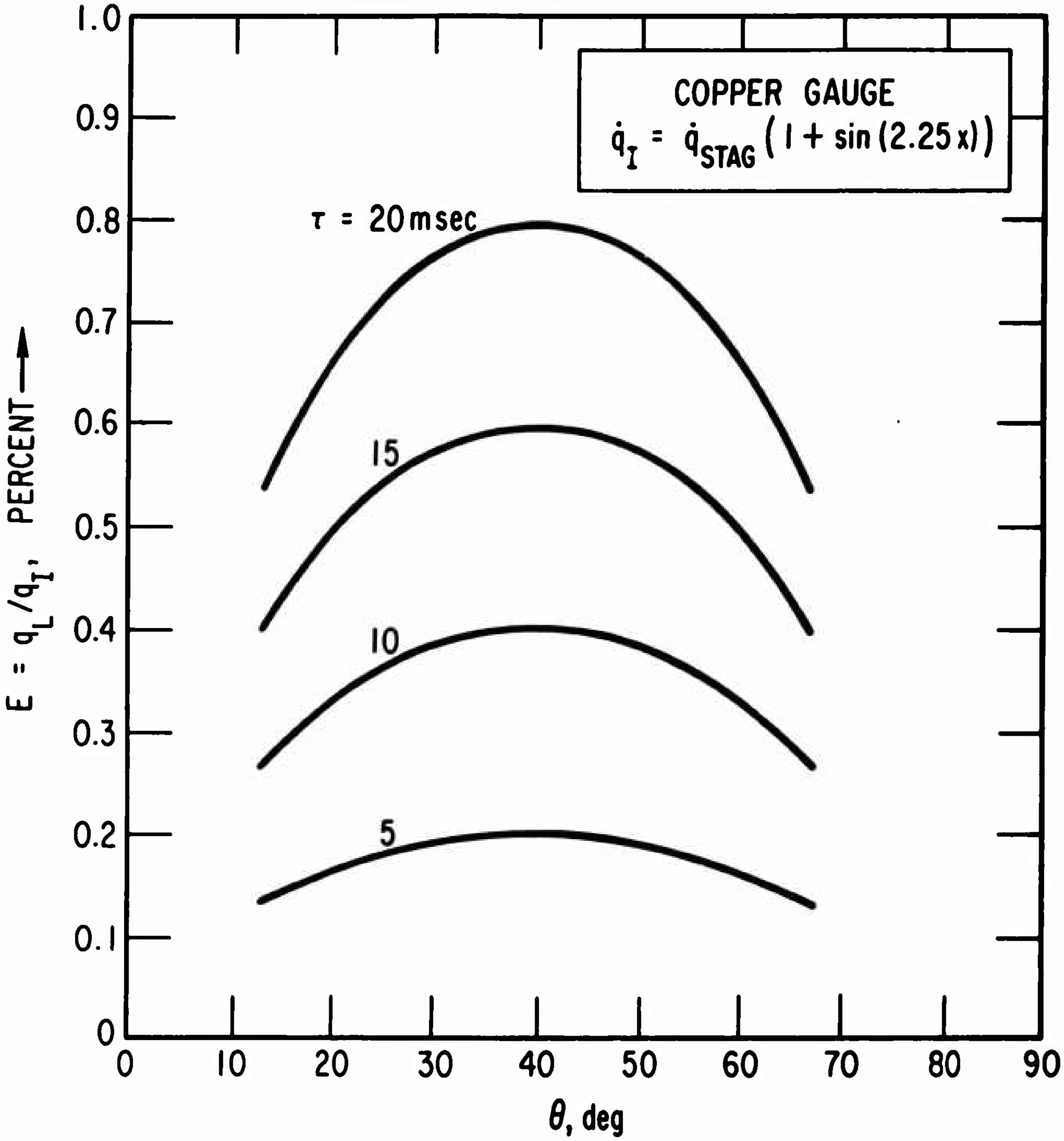

Figure 5. Conduction Error for 1 + Sine Distribution of Heat Flux

IV. EXPERIMENTAL PROGRAM

Figure 6 shows a two-dimensional model constructed according to the sketch of Figure 2. The single constantan wires are soldered to the copper strip (roughened or unroughened), and then the assembly is stretched over the lucite model with the radially located wires extending through a narrow saw cut in the model. A bond of epoxy can be applied between the copper strip and the lucite model to produce a rigid construction. The 0.003-in.-diam constantan wires terminate at junction points within the model near the sting entrance. It should be possible to extend this concept to axisymmetric models by using copper films formed to the model contours, although this may be considerably more difficult than for the strip concept shown in Figure 6.

Various techniques may be used for surface roughening of the thick film copper strips. It has been found that shot-peening of a copper strip that has been stretched over a solid metal mandrel produces a uniform random surface roughness. The strip must be annealed following the shot-peening in order to transfer it from the mandrel to a model substrate without causing gross distortions of the strip. Chemical etching and other surface roughening techniques, such as knurling and fine machining, should also be useful in this application. If the film thickness is kept large compared to the required roughness height, the rear surface thermocouple will measure an average heat flux to the surface as desired.

The gauges were radiation-calibrated by exposure to a shutter-regulated high-temperature graphite strip (Figure 7) at heat flux levels to 50 Btu/ft^2-sec to calibrate for variations introduced during thermocouple installation. A calibrated steady-state Gardon-type calorimeter was used as a standard for gauge calibration. A sliding shutter arrangement allowed generation of a pulse of radiation of varying length from as little as a few milliseconds. Both gauges were covered with a thin layer of camphor smoke to produce matching radiation absorption characteristics during calibration. Figure 8 shows a typical radiation heat flux pulse measured by a platinum thin film gauge with a built-in analog conversion from surface temperature to heat flux. The

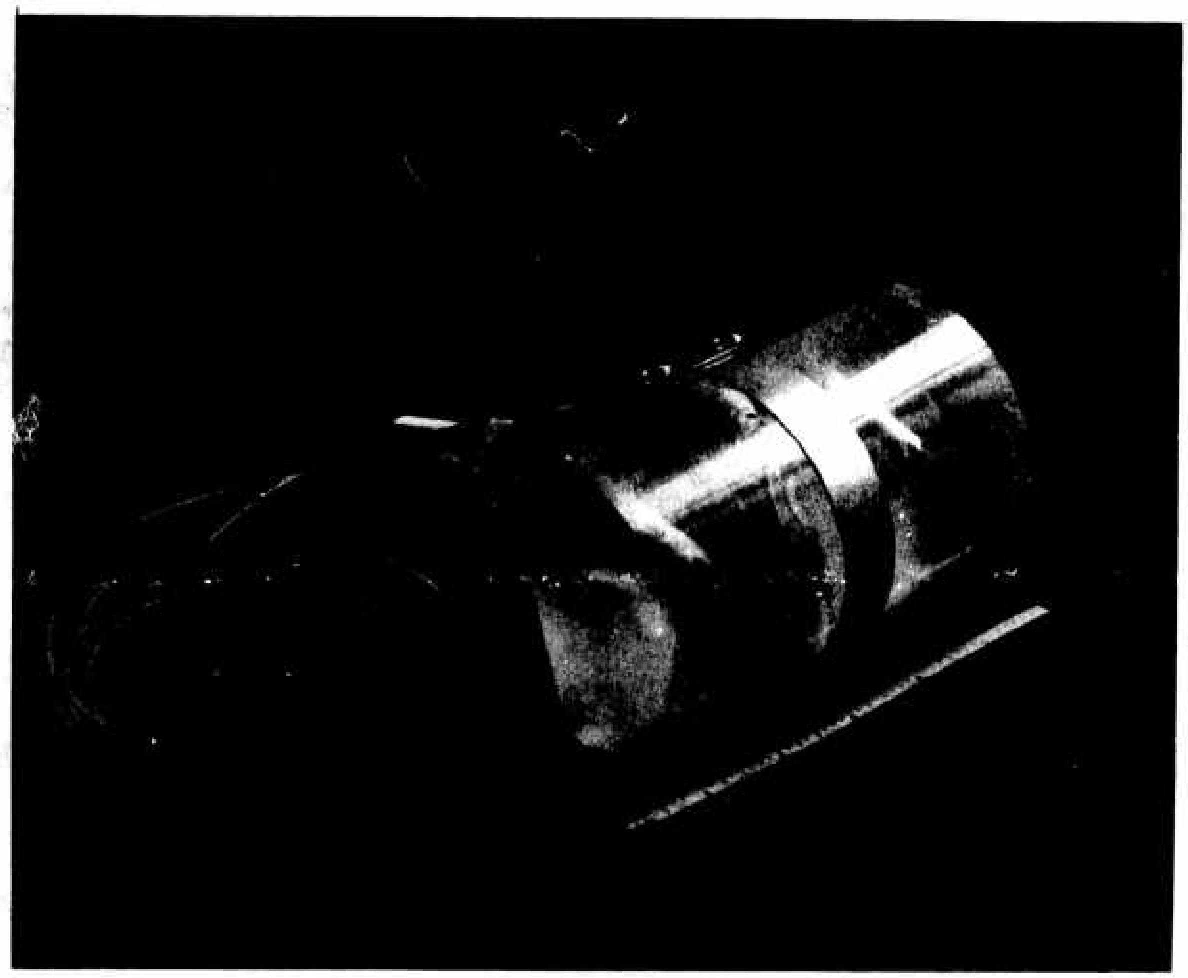

Figure 6. Two-Dimensional Shock Tunnel Gauge

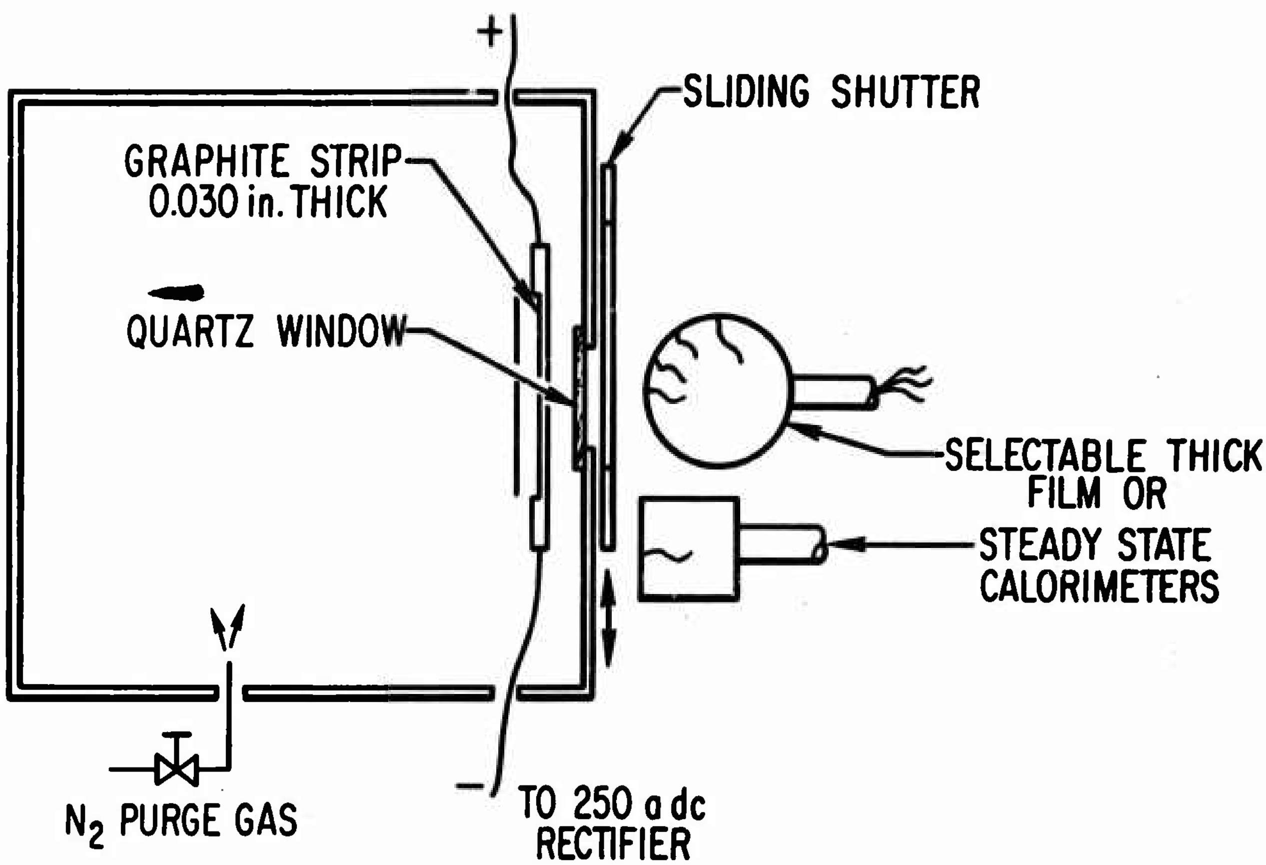

Figure 7. Heat Flux Calorimeter Calibration Source

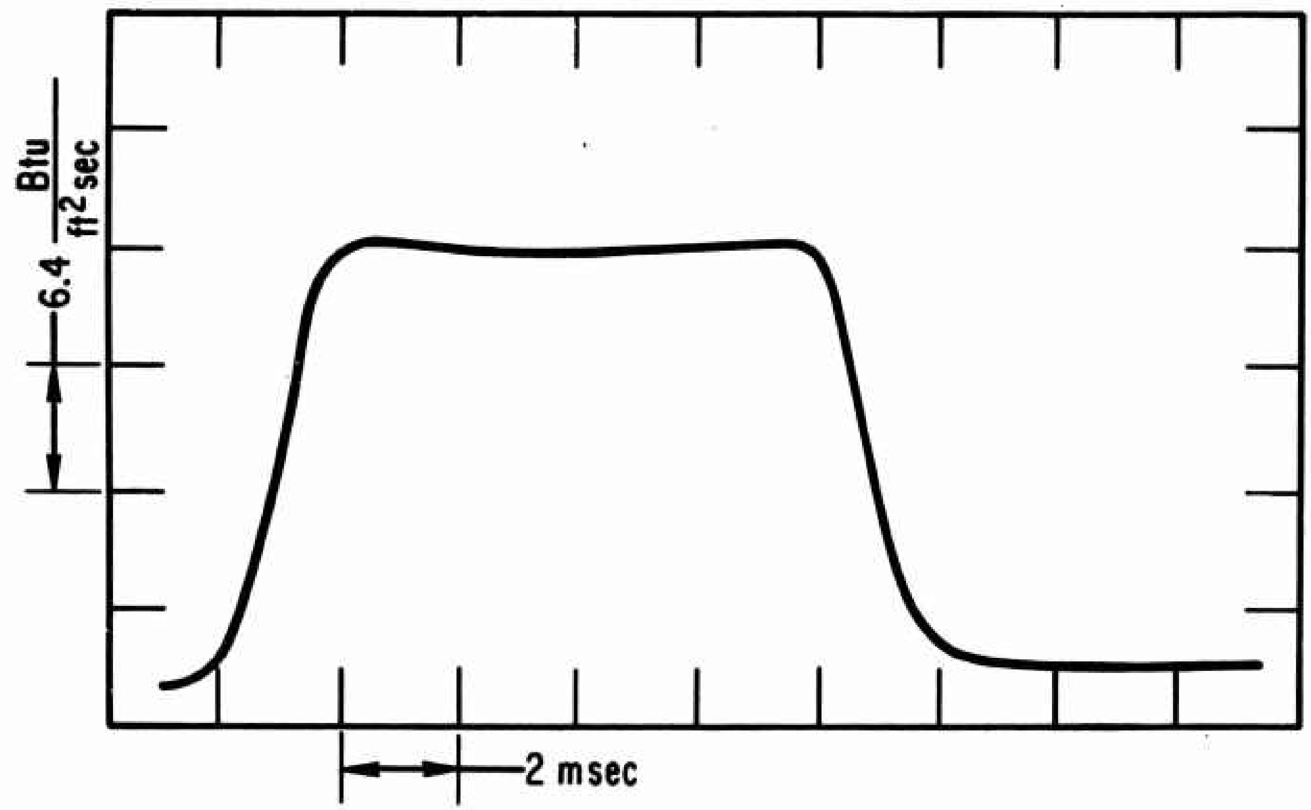

Figure 8. Heat Flux Pulse from Radiation Calibration Source

trace of Figure 9 shows the response of the copper thick film gauge during a 6-msec radiation pulse.

The test region of the high Reynolds number shock tunnel facility for which these gauges were developed is shown in Figure 10. Surface heat fluxes for 4-in.-diam models are in the range of 30 to 150 Btu/ft^2-sec at model stagnation pressures in the 1- to 3-atm range. Figure 11 shows laminar stagnation point heat flux data taken during a tunnel test of about 5-msec total duration. A heat flux of 38.5 Btu/ft^2-sec is indicated during the linear rise period and is in good agreement with the laminar flow prediction at this model checkout flow condition. Such tests have shown this gauge concept to be suitable for the shock tunnel environment, and future tests will involve investigation of roughened model heat flux distributions in higher Reynolds number flows.

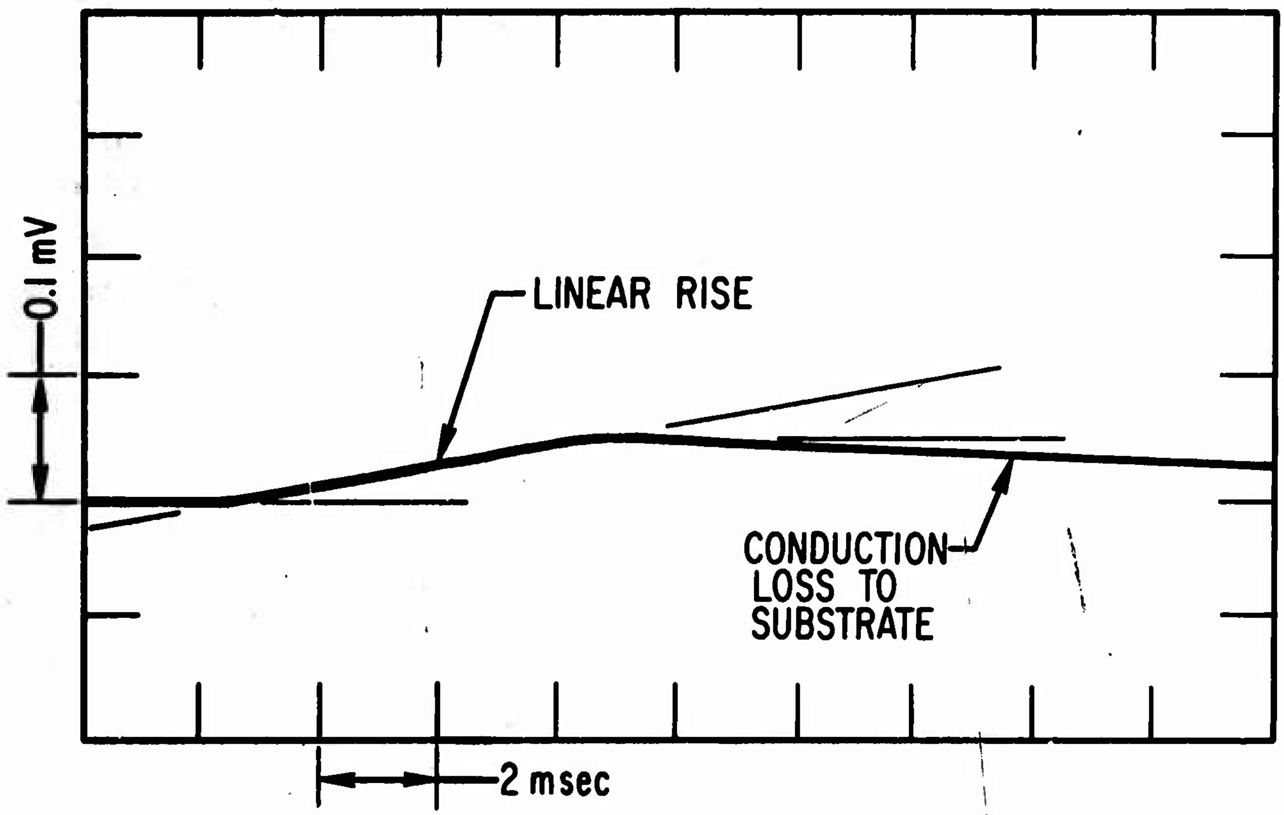

Figure 9. Calibration Output from 0.010-in. Copper Gauge

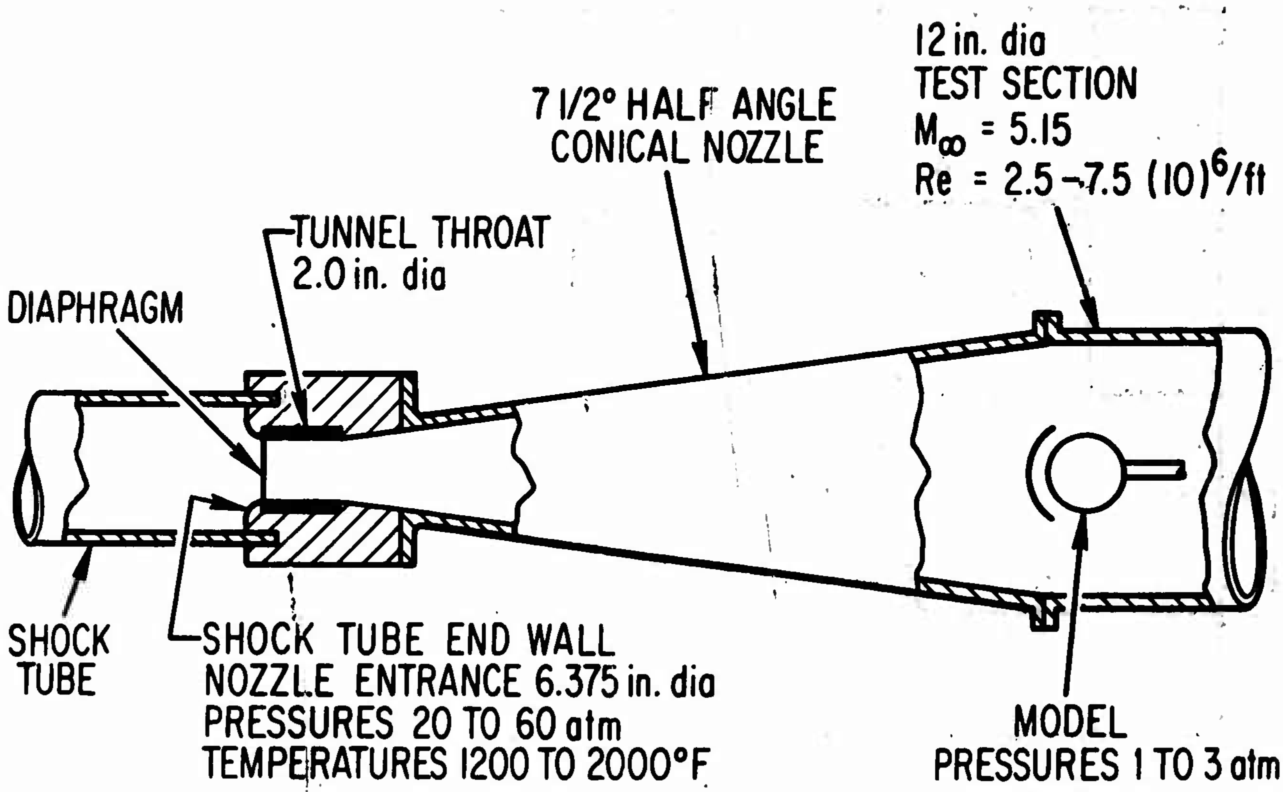

Figure 10. High Reynolds Number Shock Tunnel

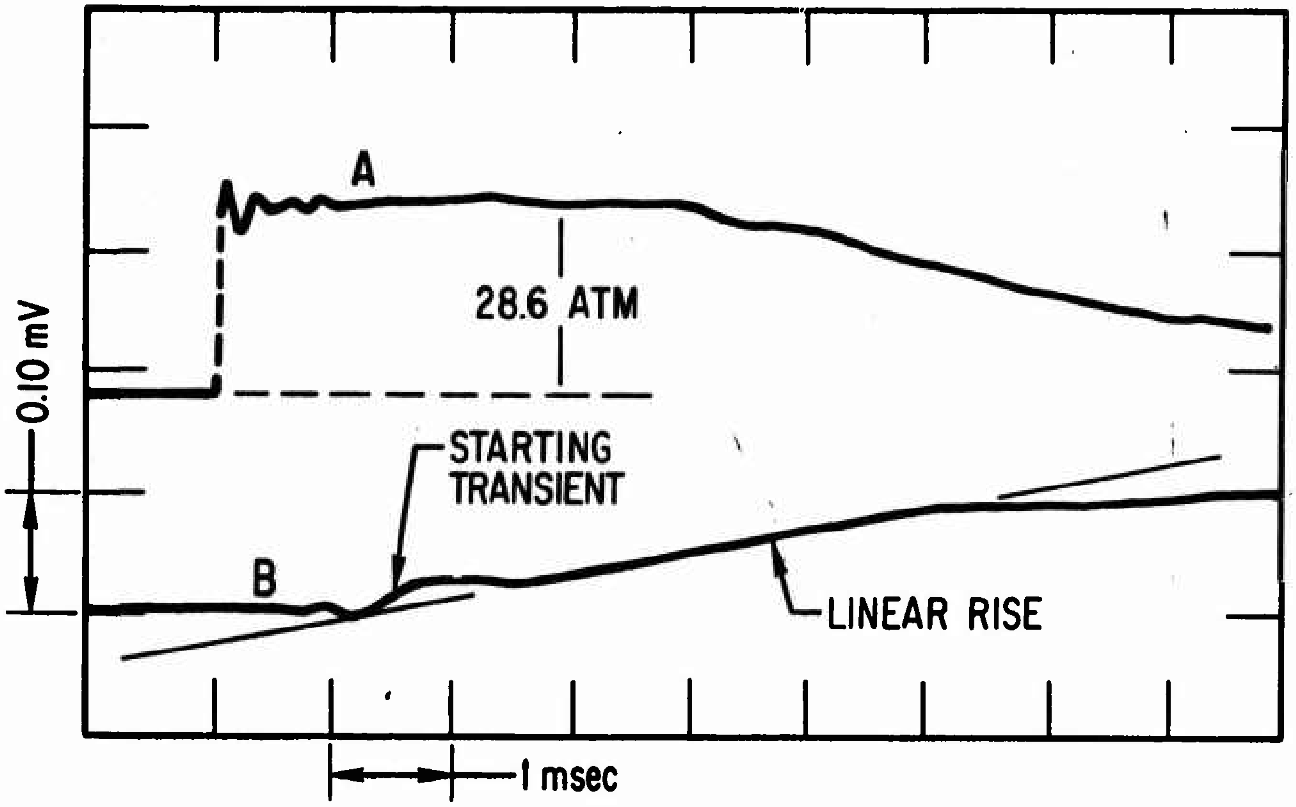

Figure 11. Shock Tunnel Test of 0.010-in. Copper Gauge on Lucite Model

V. CONCLUSIONS

A continuous thick film thermocouple gauge technique has been presented whereby rough wall model heat fluxes in short duration flows may be measured. It has been shown that the requirement that the film thickness be large compared to the roughness height can be met for the flows of interest. The following limitations were investigated with respect to gauge test time:

1. Response time of the gauge film and thermocouple to a step input of heat flux.
2. Output of the gauge for typical heat flux levels and available test times.
3. Conduction heat transfer errors in the gauge film resulting from heat flux gradients over the model surface and loss to the substrate.

A radiation calibration scheme has been discussed that allows fast response gauge calibration by comparison with a steady state calorimeter. Data obtained from radiation calibration and during shock tunnel tests are presented.

REFERENCES

1. H. K. Strass and T. W. Tyner, Some Effects of Roughness on Stagnation-Point Heat Transfer at a Mach Number of 2, a Stagnation Temperature of 3530°F, and a Reynolds Number of 2.5×10^6 per foot, RM L58C10, NACA Langley Field, Va. (May 26, 1958).

2. M. Cooper, E. E. Mayo, and J. D. Julius, The Influence of Low Wall Temperature on Boundary-Layer Transition and Local Heat Transfer on 2-Inch Diameter Hemispheres at a Mach Number of 4.95 and a Reynolds Number per foot of 73.2×10^6, TN D-391, NASA Langley Field, Va. (July 1960).

3. W. E. Welsh, Jr., "Shape and Surface Roughness Effects on Turbulent Nose Tip Ablation," AIAA Fluid and Plasma Dynamics Conference, San Francisco, Calif., June 16-18, 1969.

4. V. S. Avduyeskiy, and V. N. Kalashnik, Problems Associated with the Calculation of Friction and Heat Transfer in a Turbulent Boundary Layer, TT F-11, 663, NASA, Washington, D. C. (April 1968).

5. I. E. Beckwith, and J. J. Gallagher, Heat Transfer and Recovery Temperatures on a Sphere with Laminar, Transitional, and Turbulent Boundary Layers at Mach Numbers of 2.00 and 4.15, TN 4125, NASA, Langley Field, Va. (December 1957).

6. K. T. Stetson, "Boundary Layer Transition on Blunt Bodies with Highly Cooled Boundary Layers," J. Aerospace Sci. 27, (2), (1960).

7. J. W. Kurzrock, Selection of Surface Thermometers for Measuring Heat Flux, Report No. 124, Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y. (February 1963).

8. R. L. Ledford, W. E. Smotherman, and C. F. Kidd, "Recent Developments in Heat-Transfer Rate, Pressure and Force Measurements for Hotshot Tunnels," Proc. 2nd Intern. Cong. Instrumentation Aerospace Simulation Facilities, Stanford University, Aug. 29-31 (1966).

9. P. H. Rose, "Development of the Calorimeter Heat Transfer Gauge for Use in Shock Tubes," Rev. Sci. Instr. 28, 557-564 (1958).

10. R. L. Ledford, A Device for Measuring Heat Transfer Rates in Arc-Discharge Hypervelocity Wind Tunnels, AEDC-TDR-62-64, Arnold Engineering Development Center, Arnold Air Force Station, Tenn. (May 1962).

11. K. E. Starner, "Use of Thin-Skinned Calorimeters for High Heat Flux Arc-Jet Measurements," Instr. Soc. Am. 7, 181-186 (1968).

12. D. R. Burnett, "Transient Temperature Measurement Errors in Heated Slabs for Thermocouples Located at the Insulated Surface," J. Heat Transfer 83, 505-506 (1961).

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13. ABSTRACT

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Abstract (Continued)

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